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Characterization of Waveguide Photonic Crystal Reflectors on Indium Phosphide Membranes

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Abstract—We present waveguide photonic crystal reflectors on the InP-membrane-on-silicon (IMOS) platform, and a method to accurately measure the reflectivity of those reflectors. The photonic crystal holes are patterned on a waveguide using electron-beam lithography and etched through the waveguiding layer to create a broadband distributed Bragg reflector. We show simulations of these reflectors and experimental results of fabricated devices, both showing a high, free-to-choose reflectivity, and high quality factor Fabry-Pérot cavities. We experimentally show reflectivities higher than 95% for the reflectors and a quality factor as high as $15,911 \pm 511$ for a Fabry-Pérot cavity, using reflectors with a length of only 4 microns. For the first time, to our knowledge, two methods for measuring the reflectivity are used for characterization of on-chip reflectors to accurately determine the reflection. The first method is based on analysis of the transmission through a Fabry-Pérot cavity, the second is based on a direct four-port measurement of the reflector. A systematic error is made in both methods, resulting in an upper and lower boundary for the actual reflection coefficient.

Index Terms—Photonic integrated circuits, nanophotonics, photonic crystals.

I. INTRODUCTION

PHOTONICS have been used in data communication since the early 1980s. The high bandwidth capabilities of optical fibers have made them an alternative to traditional copper cables that could not be overlooked. New technologies, e.g. wavelength division multiplexing and advanced digital coherent technologies pushed the popularity of optical communication even further. Historically, optical communication was used for long distance communication or for bandwidths exceeding the capabilities of electronics. More recently, optical communication is preferred over electronics also for shorter distances, e.g. rack-to-rack interconnects in data centers. Low power consumption and integratability with electronics is becoming increasingly important in these systems. Nanophotonic platforms, e.g. the silicon on insulator (SOI) platform, offer a solution. The InP-membrane-on-silicon (IMOS) platform [1] offers the possibility for low power-consumption,

Fig. 1. Cross section of a typical waveguide on the IMOS platform.

homogeneously integrated lasers and integration with CMOS electronics.

The IMOS platform consists of a 300 nm thick membrane of InP, which corresponds to the core thickness in the nanophotonic waveguides, bonded by benzocyclobutene (BCB) to a silicon carrier wafer. The thin membrane and high index contrast enable tight light confinement and small footprint devices and waveguides, the latter being 400 nm wide for the passive waveguides. A cross section of a typical waveguide on the IMOS platform is shown in Fig. 1. A detailed description of the fabrication process of IMOS devices is given in Section IV. To achieve low power-consumption for lasers, the cavity has to be designed carefully, and reflectors with high reflectivity are necessary to reach a high quality factor. For this purpose, we designed a photonic crystal reflector made in a nanophotonic wire by patterning elliptical holes on the waveguide. The reflector has also been used in other applications, e.g. reflection-type arrayed waveguide gratings [2]. Photonic crystal reflectors have been widely used, e.g. for creating high quality factor cavities. Zain *et al.* [3] demonstrated a quality factor of 74,000 for a cavity length of 5 μm in 2010. Two years earlier, they also demonstrated quality factors of 149,000 for micro-cavity structures [4]. In 2016, Crosnier *et al.* [5] demonstrated a quality factor higher than 100,000 for nanocavities in indium phosphide based structures on silicon on insulator waveguides. The cavities we designed were not optimized for high quality factor, since the cavity is merely a tool for measurement of the reflectivity of the designed reflectors. Therefore, the reported quality factor is lower than the state-of-the-art.

Furthermore, we present a way to accurately measure the reflectivity of the fabricated reflectors. Therefore, we refer to the previous work in the PhD thesis of Pello [6], where he presented a method for directly measuring the reflectivity of

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Fig. 2. Top view of photonic crystal reflectors. Left: reflector in 400 nm wide waveguide. Right: reflector in 700 nm wide waveguide.

highly reflective components using a four-port measurement technique. We combine this method with Fabry-Pérot cavity measurements to achieve accurate measurement of the reflectivity of a single reflector.

II. DESIGN

The photonic crystal reflector is implemented with elliptical holes to periodically change the refractive index in the waveguide. Partial reflections on the transition between holes and waveguides are added in phase to provide a strong reflection. Due to the large index contrast only a limited number of holes is needed, resulting in a small and broadband reflector. For the initial prototypes, a taper is required for the transition between the regular waveguide (400 nm wide) and the wider waveguide section (700 nm wide) in which the holes are patterned. The shape of the holes is optimized for the waveguide width and the wavelength. The effective refractive index of the mode changes with waveguide dimensions as well as with the wavelength. A 3D FDTD simulation tool is used to determine the optimized hole dimensions for the 700 nm waveguide width. Further optimizations in the simulations have shown that a reflector with similar performance can be designed in the 400 nm wide waveguides, which means the length of the device can be reduced by removing the requirement for adiabatic tapers. The tapers are designed such that the excitation of higher order modes is avoided. For both widths, the designs are shown in Fig. 2 and the corresponding dimensions for both designs are shown in Table I.

TABLE I
DIMENSIONS OF THE DESIGNS SHOWN IN FIG. 2

Waveguide width	400 nm	700 nm
Hole pitch	450 nm	360 nm
Hole diameter (x)	173 nm	270 nm
Hole diameter (y)	248 nm	180 nm

Fig. 3. Simulation results for the reflectivity of photonic crystal reflectors in 400 nm wide waveguides. N is the number of holes.

Fig. 4. Simulation results for the reflectivity of photonic crystal reflectors in 700 nm wide waveguides. N is the number of holes.

III. SIMULATIONS

The photonic crystal reflectors are simulated using a three dimensional finite-difference time-domain (3D FDTD) software tool. For both designs shown in Fig. 2 the number of holes was varied in the simulations. The dimensions of the holes is kept similar to the values shown in Table I. The hole sizes for the two holes on both ends of the reflector are reduced to 60% for the first hole and 80% for the second hole, with respect to the standard hole size. This is done to create a smooth transition between the waveguide and the reflector.

The simulation results for the reflectivity of the photonic crystal reflector in 400 nm wide waveguides and in 700 nm wide waveguides are shown in Fig. 3 and in Fig. 4, respectively. For the 700 nm wide reflector, we can

Fig. 5. Bonding process flow used for fabricating IMOS passive devices. (a) pre-bonding (b) after bonding and removal of the InP substrate and etch-stop layer.

achieve more than 99% reflectivity over a large bandwidth. For the 400 nm wide reflector, high reflectivity can be achieved, but for a lower bandwidth. Simulations show high dependency on deviation of hole dimensions for the 400 nm wide reflectors, where the 700 nm wide reflectors show significantly lower dependency. For example, for a 40 nm deviation in hole diameter, the 400 nm wide reflector's reflectivity is less than 50% at a wavelength of 1550 nm, where the 700 nm wide reflector is barely impacted by the deviation. The insertion loss of the reflector is simulated, and is below 0.1 dB in the wavelength range between 1500 nm and 1600 nm, for all values of N shown in Fig. 4.

IV. FABRICATION

The photonic crystal reflectors are designed on the IMOS platform. A brief summary of the fabrication process of the chip used to obtain the reported results is described in this section. Typically, we start by bonding an InP wafer to a silicon carrier wafer as shown in Fig. 5. Silicon dioxide is deposited on both wafers for improved adhesion, and benzocyclobutene (BCB) is spun on the silicon carrier wafer. In a wafer bonding tool, pressure and high temperature are applied, and the wafers are bonded together. After the bonding, the indium phosphide substrate and indium gallium arsenide etch-stop layers are removed by selective wet-chemical etching. Remaining is the 300 nm thick InP membrane, as shown in Fig. 5(b).

After bonding, IMOS devices are fabricated in the membrane using electron beam lithography (EBL), to define etched regions. A simplified version of the process flow is shown in Fig. 7. In step (a), first a layer of 50 nm silicon nitride is deposited on the indium phosphide membrane. ZEP photoresist is spun on the wafer, and the exposure is done using

Fig. 6. Scanning electron microscope (SEM) image of a fabricated photonic crystal reflector.

electron beam lithography, as shown in Fig. 7(a). The pattern is then transferred to the silicon nitride mask using reactive ion etching, and the photoresist is removed, which is shown in Fig. 7(b). Finally, a different reactive ion etching process is used to transfer the patterns in the silicon nitride mask to the indium phosphide, after which the silicon nitride mask is removed. This results in patterned devices in the indium phosphide membrane, as shown in Fig. 7(c). A scanning electron microscope (SEM) image of the fabricated photonic crystal reflector in a 700 nm wide waveguide is shown in Fig. 6.

V. MEASUREMENTS

We present two methods for characterization of the photonic crystal reflectors. For the first method, the transmission over a wavelength range of around 100 nm through a Fabry-Pérot cavity is measured. From the spectral resonances, the reflectivity can be derived, as well as quality factor, finesse and free spectral range (FSR) of the cavity as explained in Section V-A1. With the second method, the reflection is measured directly, as explained in Section V-A2.

A. Methodology

1) *Fabry-Pérot Method*: For the measurements with this method, 50 μm long Fabry-pérot cavities are created by using two identical photonic crystal reflectors, as schematically shown in Fig. 8. The transmission spectrum for this structure is measured, from which the FSR and full-width at half-maximum (FWHM) of the resonance peaks can be obtained [7]. The finesse F is then given by

$$F = \frac{\text{FSR}}{\text{FWHM}}, \quad (1)$$

and the reflection coefficient R is obtained by

$$R = \sqrt{e^{-\frac{2\pi}{F}}}. \quad (2)$$

Furthermore, the quality factor Q of the cavity can be calculated by

$$Q = \frac{\lambda}{\text{FWHM}}. \quad (3)$$

Fig. 7. Post-bonding process flow used for fabrication of IMOS passive devices.

Fig. 8. Schematic of Fabry-Pérot characterization structure, used to measure the reflection of the photonic crystal reflector, as well as several figures of merit of the cavity.

A systematic error is made by neglecting the propagation loss in the cavity. Typically, the propagation loss in 400 nm wide waveguides is 5-10 dB/cm. For 700 nm wide waveguides, the loss was not measured, but is expected to be lower, due to lower scattering from sidewall roughness. Considering the length of the cavity that is used, it is reasonable to neglect the propagation loss. Consequently, the calculated reflectivity from the resonance peaks will be lower than the actual reflectivity of the reflector.

2) *Direct Method*: With this method, the reflection of the photonic crystal reflector is measured directly, using a four port characterization structure, which is schematically shown in Fig. 10. This method is preferred over a two port structure, since the coupling and waveguide losses can be canceled out by using the extra two ports. This becomes evident by analyzing the transmitted powers P_{ij} , with i referring to the input port and j to the output port. Firstly, the powers P_{ij} are given by

$$P_{13} = \alpha_1 \alpha_3 \alpha_{\text{MMI}}^2 R P_{\text{in}}, \quad (4)$$

$$P_{23} = \alpha_2 \alpha_3 \alpha_{\text{MMI}}^2 T P_{\text{in}}, \quad (5)$$

$$P_{14} = \alpha_1 \alpha_4 \alpha_{\text{MMI}}^2 T P_{\text{in}}, \quad (6)$$

$$P_{24} = \alpha_2 \alpha_4 \alpha_{\text{MMI}}^2 R P_{\text{in}}, \quad (7)$$

where α_k is the loss contribution in arm k , α_{MMI} is the power transmission coefficient of the MMI (~ 0.5), P_{in} is the power coupled from the input fiber, R is the reflection coefficient of the reflector, and T is the transmission coefficient of the reflector. The simulated insertion loss for the device is known, which is key for this method's accuracy. Since the insertion loss is low in the simulations, we assume that it can be neglected, and $T + R = 1$ can be used, so we can write

$$B = \frac{P_{23} P_{14}}{P_{13} P_{24}} = \frac{(1 - R)^2}{R^2}, \quad (8)$$

which gives one physical solution for the reflectivity:

$$R = \frac{1}{1 + \sqrt{B}}. \quad (9)$$

It can be seen that the loss in any of the arms is canceled out by using this four port method. A systematic error is made, however, by neglecting the insertion loss of the reflector. Therefore, the actual reflectivity could be lower than the measured reflectivity. To identify the effect of the contribution of the insertion loss of the reflector, we consider a loss contribution in the reflection and transmission of the reflector separately. This will provide the lower and upper bound of the reflectivity versus the loss of the device. For a loss contribution in the transmission, we get

$$B_{\text{upper}} = \frac{\alpha_T^2 (1 - R)^2}{R^2}, \quad (10)$$

where α_T is the coefficient due to the loss in the transmission ($0 < \alpha_T < 1$). This results in the following upper bound for the reflectivity:

$$R_{\text{upper}} = \frac{R}{R + \alpha_T (1 - R)}. \quad (11)$$

Similarly, the lower bound for the reflectivity is obtained, with

$$B_{\text{lower}} = \frac{(1 - R)^2}{\alpha_R^2 R^2}, \quad (12)$$

resulting in

$$R_{\text{lower}} = \frac{\alpha_R R}{(\alpha_R - 1)R + 1}. \quad (13)$$

The lower and upper bound for the reflectivity plotted against the insertion loss is shown in Fig. 9. We note that the impact of the insertion loss is lower for higher reflectivities. For example, for an insertion loss of 1 dB, the maximum error for a measured reflectivity of 0.9 is only $\pm 2\%$. Note that for the simulated loss of 0.1 dB the error becomes very small.

Combining the measured reflectivity obtained by the direct method and by the Fabry-Pérot method, an upper and lower bound for the actual reflectivity is obtained, respectively.

 Fig. 9. Lower and upper bound for the reflectivity against the coefficient α .

Fig. 10. Schematic of four port characterization structure, used to directly measure the reflection of the photonic crystal reflector.

 Fig. 11. Measured transmitted power through a Fabry-Pérot cavity consisting of photonic crystal reflectors with $N = 10$ holes.

B. Results

1) *Fabry-Pérot Measurement Results:* The transmission through a Fabry-Pérot cavity created by two photonic crystal reflectors is measured. The results for the reflectors in 700 nm wide waveguide structures are presented. From the obtained data, several parameters can be calculated, such as the finesse F , the reflection coefficient of a reflector R , and the quality factor of the cavity Q . An attenuator with 30 dB attenuation is used to reduce the input power, to prevent thermal or other non-linear effects due to high optical power in the cavity. An example of a transmission measurement through the cavity is shown in Fig. 11.

 Fig. 12. Reflection coefficient for a single photonic crystal reflector in 700 nm wide waveguide structures with N holes. Error bars are included for indication of the measurement accuracy for the reflector with 5 holes. The error bars are not shown for the other reflectors to prevent cluttering.

 Fig. 13. Quality factor for a Fabry-Pérot cavity in 700 nm wide waveguide structures with N holes for the two reflectors. Error bars are not included, maximum uncertainty is 4%.

Fitting to each individual peak in the obtained spectra allows for extraction of the full-width at half-maximum (FWHM) of the peaks. For each peak, the reflection coefficient of a single photonic crystal reflector is calculated, which is shown in Fig. 12. As expected, and shown in the simulation results in Fig. 4, the measured reflection coefficient increases with the number of holes. Values for the reflection coefficient of over 99% are however not achieved here, which can be explained by the systematic error in the measurement method, which is explained in Section V-A1.

The quality factor of the measured cavities is shown in Fig. 13. We demonstrate a cavity with a quality factor of almost 16,000. The propagation loss and reflection coefficient of the reflectors are limiting factors for the quality factor.

2) *Direct Measurement Results:* The direct measurement method using the four-port characterization structures is used to directly measure the reflectivity of a single photonic crystal reflector. The transmissions obtained for a photonic crystal reflector with $N = 11$ holes is shown in Fig. 14.

Fig. 14. Measured power for four-port characterization structure with $N = 11$ holes.

Fig. 15. Reflection coefficients for photonic crystal reflectors with N holes, calculated from measurements obtained using the four-port characterization structure.

Using the method explained in Section V-A2, the reflection coefficient of the reflector can be obtained, which is shown in Fig. 15. The periodic fringes on the measurement data and the calculated reflections are caused by the cavities created by back-reflections of the grating couplers, which provide the coupling between the fibers and the circuit, and the reflector itself.

3) *Comparison:* Looking at the reflection coefficients obtained by the two presented methods in this paper, shown in Fig. 12 and Fig. 15, we observe higher reflection coefficients for the direct method. This can be explained by the systematic errors that are made in the two methods. For the Fabry-Pérot measurement, the systematic error is made by not taking the propagation loss in the cavity into account. For these measurements, the net reflection of the reflectors is measured, thus the measured reflection will be slightly too low. For the direct measurements, the insertion loss is neglected, resulting in a higher measured reflection coefficient. By using both methods, we find an upper and lower bound for the

TABLE II
COMPARISON OF THE TWO MEASUREMENT METHODS AND THE
SIMULATED REFLECTION COEFFICIENT AT
A WAVELENGTH OF 1532 nm

# of holes	R FP method	R direct method	R simulated
5	0.871	0.902	0.932
7	0.932	0.968	0.972
9	0.944	0.990	0.991

reflection coefficient of the photonic crystal reflector, as shown in Table II. The simulated values are slightly higher than the measured value, due to stringent fabrication tolerances for these prototypes.

With the direct method, reflectors with high reflectivity can be measured easily, whereas with the Fabry-Pérot method, we noticed that for a higher number of holes, and hence for a higher reflectivity, the transmitted power is too low to be detected.

VI. CONCLUSION

Photonic crystal reflectors on the InP-membrane-on-Silicon (IMOS) platform are designed and fabricated, showing reflection coefficients of over 95% experimentally. We show simulation results and two methods for measuring the reflection coefficient. The small difference between the measured values is caused by systematic errors in both of the techniques. Using both techniques for a similar reflector gives a reliable interval for the actual value of the reflection coefficient for that reflector. Using the designed reflectors, a 50 μm long Fabry-Pérot cavity with a quality factor of almost 16,000 is also demonstrated.

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